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OBSERVATION OF TWO PHOTONS IN n-p CAPTURE*

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ABSTRACT

This paper reports on the observation of two gamma rays in coincidence following the capture of subthermal neutrons by protons in water. The measured branching ratio of two-gamma events to single gamma events in the energy range of 600keV to 1620keV was found to be 0.0011 ± 0.0002. Possible sources of systematic error are also considered.

INTRODUCTION

The background for this experiment lies in the long-standing discrepency between the experimental and theoretical values for the cross section of thermal neutron capture by protons. A short time ago, R. J. Adler[1], following a suggestion by Breit and Rustgi[2] concerning a possible non-orthogonality in the deuteron wave functions, showed that the discrepency could be explained if the overlap in the normally-orthogonal continuum and ground-state wave functions was very large. A secondary consequence of this argument was a large enhancement of the probability of emitting two gamma rays during the de-excitation to the ground state of the deuteron. The expected cross section for two-gamma emission was around 40 microbarns.

Calculations showed that such a measurement would be feasible if large NaI(Tl) crystals were used in a close-geometry arrangement. Accordingly, as P. D. Miller and I were about to embark on a trip to Grenoble, France to carry out an experiment to look for the electric dipole moment of the neutron at the high-flux reactor, Institute Max von Laue - Paul Langevin, we took along the necessary electronics and detectors in case the occasion should arise to look for the two gamma rays. Following a breakdown of our neutron spectrometer, we got the opportunity to carry out the desired measurement with the collaboration of our colleagues Paul Perrin of the CEN, Grenoble and Glaude Guet from the University of Grenoble.

EXPERIMENTAL ARRANGEMENT

We had designed the experiment for a sensitivity of about 10 microbarns (some 30000 times smaller than the usual n-p capture cross section). The detector arrangement is shown in Figure 1 where the two 12cm by 12cm crystals are depicted facing each other at a distance of about 5cm. They were mounted on selected RCA 4522 high-speed high-resolution photomultiplier tubes, and contained in an iron and lead housing to provide magnetic shielding for the phototubes and to reduce the number of events not originating in the target volume, which was midway between the two crystals. The target was about 2 cm^3 of distilled water sealed in a bag of 0.006mm thick Mylar placed inside a container made of 2mm-thick LiF ceramic enriched in ^6Li. Thus any neutrons not captured by the water or Mylar were absorbed by the lithium with the emission of very few gamma rays. This precaution shielded the crystals from scattered neutrons, and practically eliminated all background radiation from neutron capture in surrounding materials.

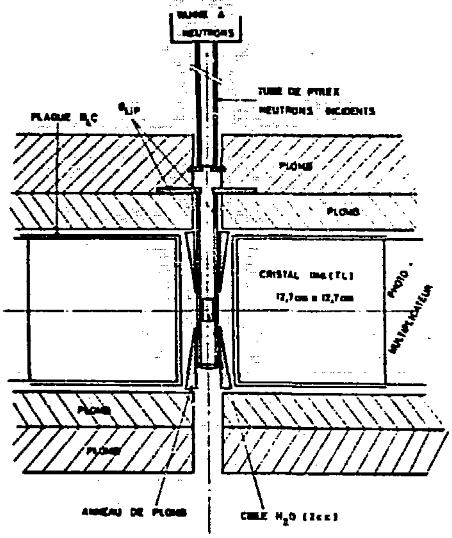

Figure 1. Arrangement of detectors and shielding.

The neutron beam from the high-flux reactor was conducted to the target region by a 5m glass tube about 8mm in diameter. The intensity was about 10^6 neutrons/sec with a mean wavelength of about 10 A. The wedge-shaped structure shown is a Compton shield made out of lead. This was expected to reduce any cross talk between the detectors, since a photon crossing from one detector to the other would have to pass through about a centimeter of lead. (Data were also taken with this shield removed with no visable change in the rate of coincidences.)

Figure 2 is a schematic of the electronics -- a typical slow-fast coincidence circuit. The fast signals (from the anode) carried the timing information; while the slow side (from the dynode) carried the spectroscopic information. The fwhm of the timing peak was 4.6 ns and a window of 9.6 ns wide was set about the peak.

The data were stored in a bi-parameter analyzer in a 64 by 64 array corresponding to coincidences as a function of energy in each detector. A typical spectrum with water as a target is shown in Figure 3. Most of the features were expected such as the first and second escape peaks in coincidence with the 511keV radiation from pair production. The unexpected feature is the diagonal band running between the two first-escape peaks (marked 1712 in the figure).

DISCUSSION OF THE DATA

A clearer view of the data in the X,Y plane is given in Figure 4. This represents a contour plot of the 64 by 64 array depicted in Fig. 3, and more details become visable. The random peak at (2220,2220) was used for normalization purposes since its volume is proportional to the width of the timing window, the reactor flux, and the total

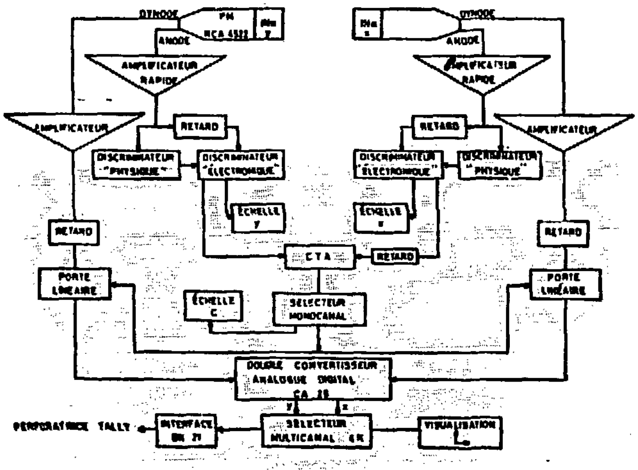

Figure 2. Schematic diagram of the data-acquisition system. The timing was provided by a time-to-amplitude converter (CTA).

counting time. The various small peaks are due to capture of the neutrons by the oxygen in the water (located at 870,1080, and 2180 keV); and various random processes such as coincidences between two first-escape photons (1721,1712), etc. The diagonal line labled

$$E_x + E_y = 2220 \text{ keV} \qquad (1)$$

was determined from calibration points (first escape peaks, the random peak at 2220,2220, and the position of the oxygen peaks), and falls along the top of the diagonal ridge. The other two diagonal lines passing near the large peaks at (511,1712) and (1712,511) represent the limits of usable data. There are two reasons for this: outside of these lines, the interference from the large peaks becomes very large; and single Compton scattering for the geometry indicated in Fig. 1 is excluded between these two lines.

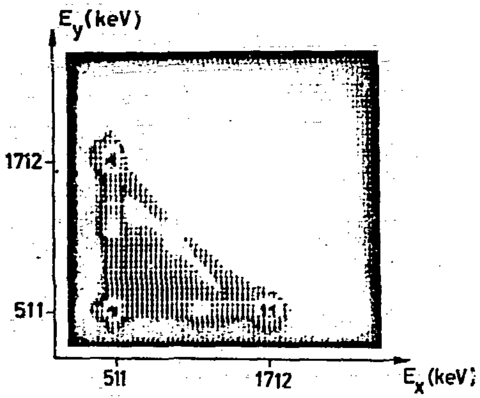

Figure 3. Data as seen on screen of analyzer. Water target used.

In order to obtain a value for the size of the effect seen the method of data reduction was to take cuts through the ridge and approximately perpendicularly to it. Such a cut is shown in Figure 5, where the vertical line drawn through the peak is computed from the calibration of the X,Y plane to satisfy Eq.(1). The area of the cut was estimated by sub-

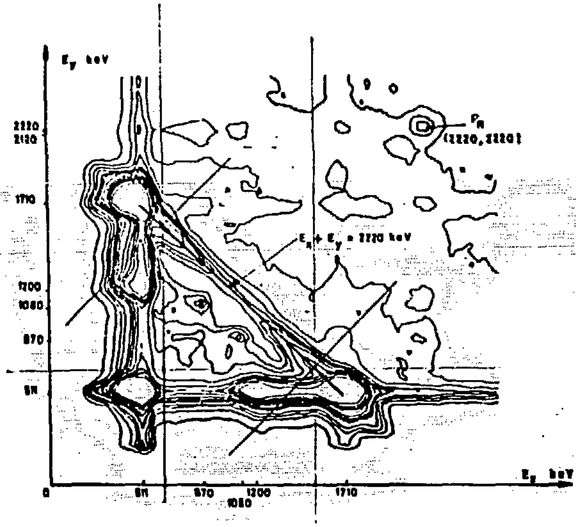

Figure 4. Contour plot of the data depicted in Fig. 3.

tracting a Gaussian at the position indicated. The width of the Gaussian was fixed by the efficiency of the detector system, and its height was adjusted until a reasonable-looking background curve was obtained.

In this way, the volume of the ridge between the two limits was obtained. The cross section thus obtained was much larger than we had expected, so we started to look for plausible explanations which could produce such an effect.

SEARCH FOR SYSTEMATICS

The most obvious systematic effect is Compton scattering; however the most likely scattering -- one scatter in either crystal -- had already been ruled out on geometrical grounds. The coincidence rate from multiple Compton scattering can been seen to be much smaller than our observed rate (about 0.7 counts/sec at a 5cm distance). Of course, an experimental check is necessary. One rather easy test is to vary the distance between the two detectors, keeping the target always in the center. Since the radius of the detector is not much smaller than the distance to the source, the usual approximation to the solid angle cannot be made. This means that the behavior of the coincidence rate as a function of distance will be different if the source of the second gamma ray is the first detector and not the target between the detectors. This behavior is shown in Figure 6, where the lower curve represents cross talk between the detectors and the upper one, the expected behavior if the target were the source of both gamma rays.

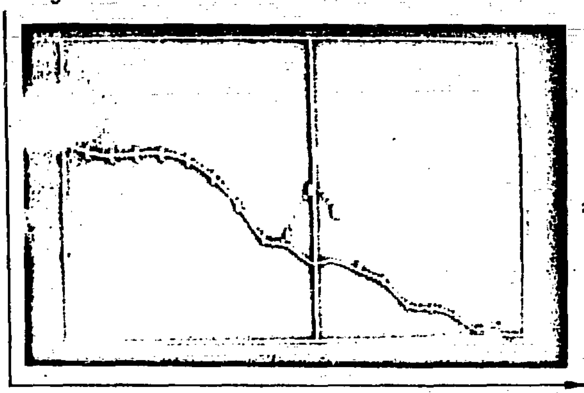

Figure 5. Upper curve is the raw data, and the lower is the estimated background under the peak.

In Figure 7 are plotted the differential cross sections as a function of the energy in detector X for three different distances between the crystals. The integrated values of each of the three distances is normalized and plotted on Fig. 6.

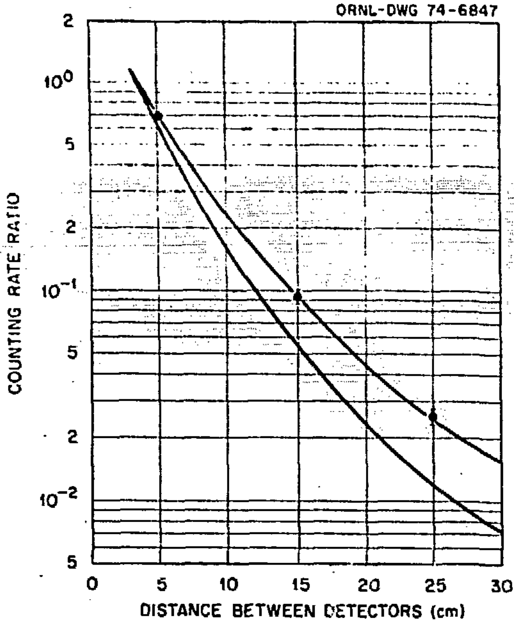

Figure 6. Counting rate ratio as a function of distance between the crystals. Lower curve represents cross talk.

The behavior of the integrated cross section clearly favors the upper curve, thus ruling out cross talk between the crystals as an explanation for the observed coincidence rate.

There are two points to be emphasized about the data shown in Fig.7: (1) The magnitude and shape of the differential cross section at the three distances are roughly similar; and (2), because of the large errors in the wings for the 15cm and 25cm data, not too much emphasis should be placed on the parabola shape. Indeed, the wings seem to drop slightly at the larger distances, perhaps indicating that a small bit of cross talk is mixed in; and the center of the plots seem to rise a bit as the distance increases. This last feature could indicate an angular correlation between the two photons. At this stage, such speculations are not warranted by the data, however.

Another test for systematic effects was to try various materials in the target region. D_2O replaced the water with the result that only the oxygen peaks were visable. An empty Mylar bag was also placed in the holder with no visable result whatsoever. These two checks also show that all of the neutrons were stopped in the ceramic target holder.

We also looked for a gamma ray source with a clean, single photon in the range of 2.22MeV; but such a search is difficult. The best we could do was a sodium-24 source which had two coincident gamma rays but about the right energy. The results of this test are shown in Figure 8, where the only evident diagonal structure is to be found

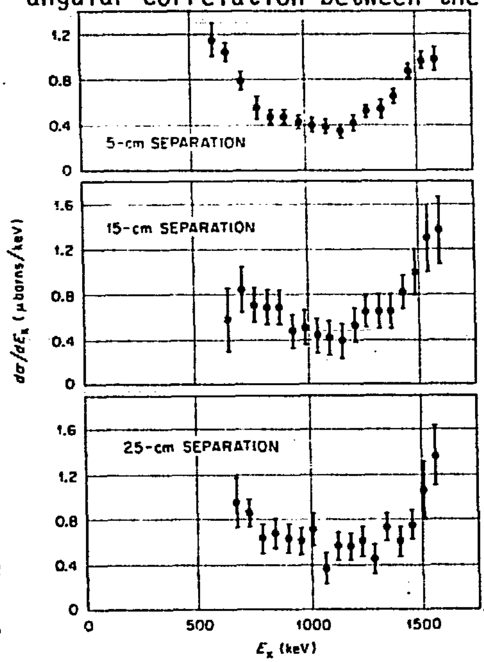

Figure 7. Differential cross cross section shown at three distances between the detectors.

is located at the edges of the plot near the points marked 2753. These short diagonal lines are probably due to Compton scattering, and are well outside the region of interest.

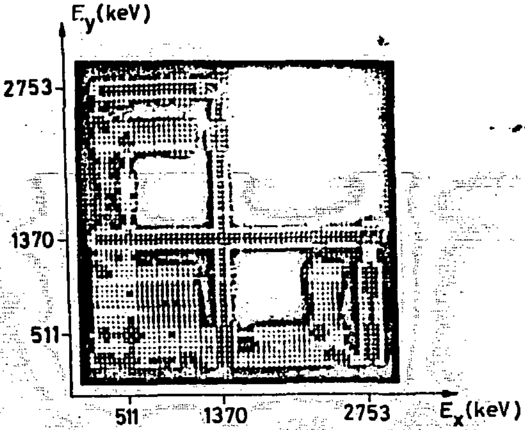

Figure 8. Spectrum with ^{24}Na as the source.

PAIR PRODUCTION

There are two ways in which pair production by the primary gamma ray at 2.22Mev could cause coincidences in the energy range considered. One would be to create pairs in the target region from the water, and the other to make pairs in either of the crystals. With the known pair-production cross sections for NaI and H_2O, the 70 000 2.22MeV photons created each second in the water will produce about 30 pairs/sec in the water, and about 470 pairs/sec in the NaI crystal at a distance of 2.5cm from the source. However, in order to have a continuous spectrum with coincidences in our region of interest, the positrons must decay in flight --in the first case, with the electron created. The second case, pair production in the detectors with a subsequent in-flight annihilation with any available electron in the crystal was pointed out by D. Alburger[3]. As might be suspected, the first case is several orders of magnitude too small to account for our signal. However, the second case is of the correct magnitude at 2.5cm if the kinematics of the in-flight annihilation are not considered. If one considers the limited range of energies used and the direction of the positron before annihilation, this process is about a factor of 5 too small at the closest distance, and even smaller at the other distances.

The conclusion is that pair production cannot explain but a small part of our signal.

SUMMARY

There seem to be two possible explanations for our signal other than an actual two-gamma decay of the deuteron continuum state. These are (1) cross talk between the detectors and (2) unexpected behavior of the 2.22MeV photon in the source region. The evidence is against both of these possibilities, but is not 100% ruled out. To completely eliminate the first possiblilty, a time-of-flight experiment on the gamma rays should be done. In this way the origin of the second gamma ray could be established as comming from the target region or not. The second possibility could involve such a process as nuclear absorption of the primary photon with the subsequent emission of more than one photon whose energies would sum to the energy of the incident gamma. To study this behavior, different materials could be placed in the target region, near the water.

I hope that this paper will stimulate other investigators to take a closer look at the n-p system and to repeat our measurements while avoiding the difficulties we found.

REFERENCES

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2 G. Breit and M.L. Rustgi, Nucl. Phys. A161, 337(1971).

3 D. Alburger, to be published.